SPALLATION DAMAGE EXPERIMENTS IN CYLINDRICAL GEOMETRY

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Abstract

Spallation damage is the process of damage in a ductile material caused by void nucleation, growth and coalescence due to states of high tensile stress. Typical experiments are conducted in a planar, uniaxial stress configuration. A convergent geometry provides a unique opportunity to study multi-dimensional stress states.

A series of 3 cylindrical spall experiments on aluminum is planned for this summer, using flux compression generators to drive the experiments. The experiments will explore the spallation damage threshold to determine effects of the cylindrical geometry. In addition, the effect of plastic work on the pressure wave profile as it moves through the material will be studied.

I. INTRODUCTION

Spallation damage can occur when a ductile material is put into a sufficiently high state of tension. The evolution of such damage can depend upon the strength, duration and profile of the shock; the initial material conditions; the deformation history; etc. Models currently available rely heavily on data produced under conditions that produce one-dimensional shock wave behavior. Using a convergent geometry provides a unique opportunity to study multi-dimensional stress states.

In 2002, using the Atlas capacitor bank, LANL performed an initial series of spallation experiments in a convergent geometry, with the goal of understanding the resulting complications in spallation effects. The current 10 experiments, conducted jointly with VNIIEF, will build on those experiments.

The first series, consisting of 3 experiments (RD-0, -1, -2), is designed to provide information on the effect of a convergent geometry on the incipient spallation regime in velocity space, as well as information on the amount of shock wave energy expended on plastic work. The liners will be in free flight (no driving current remaining) at the time of impact with the targets, to more closely duplicate flyer-plate assembly loading. The driver is a helical flux compression generator designed and manufactured by VNIIEF. The system will also include a current opening switch, a current interrupter and a means to shield the experimental load from the explosive debris.

LANL designed and manufactured the load assemblies for the experiments. This paper presents the designs of the 3 load assemblies and preliminary calculations of the effect of load-region current variation on physical properties of interest in the material, such as velocity.

II. LOAD ASSEMBLY

A. Physics Objectives

The physics objective of RD-0 and -1 is to explore the incipient spallation region, providing information on void generation, growth and coalescence. This data will be used to baseline the Tonks model for onset of spallation in ductile metals [1], which is intended for future inclusion in the Tepla model of spallation [2]. The degree of spallation that develops in a material depends on the impact velocity of the liner. These experiments will be used to determine whether the velocity range for incipient damage in aluminum 1100-O has changed in the cylindrical configuration from planar gas gun experiments (204 m/s +/- 3%). In addition, RD-0 will include a liner with no target to check that circuit models are adequately capturing the physics of the generator.

The physics objective of RD-2 is to explore how plastic work and other dissipative effects influence propagation of a shock wave in a material. This will be accomplished by applying identical impacts to two targets of different thickness, resulting in different amounts of plastic work expended and different degrees of cylindrical convergence experienced. The ability to field two experiments in one assembly greatly facilitates this objective. This physics issue was identified in the 2002 Atlas series.

B. Load Design

Changeable load region quantities include the thickness and location of the liner, target and return conductor, as well as the height of the assembly. Once these are fixed, the only system variable is the current produced by the generator. The desired outcome is a specified liner velocity at a given radius, with a short liner flight time before impact. In addition, to more closely simulate flyer plates, it is desirable for the liner to be "coasting" with no driving current available at the time of impact.

All three experiments have identical 2 mm thick liners, with an outer radius of 50 mm, the same as the 2002 Atlas experiments. The liner is one piece between the upper and lower glide planes.

Each load assembly contains 2 experimental regions, separated by a middle glide plane. The liner impacts this glide plane simultaneously with the first target. The outer radii of the targets are based on two considerations. First, calculations indicated that the liner travels approximately

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005	**N/A**	**-**

4. TITLE AND SUBTITLE **Spallation Damage Experiments In Cylindrical Geometry**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory, P.O. Box 1663, MS-B259 Los Alamos, NM 87544 (USA)**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013.

14. ABSTRACT

Spallation damage is the process of damage in a ductile material caused by void nucleation, growth and coalescence due to states of high tensile stress. Typical experiments are conducted in a planar, uniaxial stress configuration. A convergent geometry provides a unique opportunity to study multi-dimensional stress states. A series of 3 cylindrical spall experiments on aluminum is planned for this summer, using flux compression generators to drive the experiments. The experiments will explore the spallation damage threshold to determine effects of the cylindrical geometry. In addition, the effect of plastic work on the pressure wave profile as it moves through the material will be studied.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2 mm while slowing from 210 m/s (upper end of incipient spall velocity range) to 198 m/s (lower end of incipient spall velocity range), independent of the peak current. Second, impact should occur shortly after the current has returned to zero (after peak velocity).

RD-0 contains 1 target with an outer radius of 44 mm (4 mm liner run before impact). RD-1 contains 2 targets with outer radii of 43 and 45 mm (5 and 3 mm liner run, respectively). As mentioned previously, this difference in outer radii effectively brackets the incipient spall velocity range. Also, one slightly larger and one slightly smaller target in RD-1 allows for another attempt at the targeted velocities, in case RD-0 does not return the expected results. All 3 targets have a thickness of 20 mm.

RD-2 has 2 targets with the same outer radius (46 mm), providing identical impact conditions. The 20 mm thick target matches the previous experiments, while the 10 mm thick target addresses the plastic work question. Since the desired effect can be seen at any velocity, an impact velocity of 215 m/s was chosen for RD-2, slightly above the incipient spall velocity range. If necessary, the thicker target in this experiment can also be used to provide an additional data point for the incipient spall velocity range.

The return conductor inner radius of 52 mm is a compromise between the desire to keep the load-region inductance as low as possible and the desire to have space to assemble the load over the 1.5 mm thick insulator. The return conductor is 5 mm thick. Calculations indicate that the return conductor moves approximately 3 mm.

Several of the design features of the successful 2002 Atlas experiments were retained in the RD series. The copper glide planes have a 4.5° slope. The targets include momentum traps [3] to prevent reflected axial release waves from loading the sample area, preserving a purely radial loading of the sample. The height of the targets will remain the same, as will the method of connecting the targets to the glide planes using O-rings. Both the liners and targets are made of 1100-O aluminum, produced by an extrusion process which results in a grain structure which is slightly elongated in the axial direction.

C. Diagnostics

Three absolutely essential diagnostics are used in these experiments. Dual-interferometer point VISAR will accurately measure the velocity of the RD-0 bare liner and target free surface shock break out and ensuing velocity, to compare to code calculations. Metallographic analysis will study the extent of damage in and near the spall plane of recovered targets, for further development of the Tonks spall initiation model. Faraday loops will measure currents in the generator region, the transmission line and the load region, to compare with circuit models.

Due to the anticipated incipient nature of the damage in these experiments, the 2 available dynamic, time-resolved radiographs will be used primarily to obtain information about the motion of the liner.

III. CALCULATIONS

Calculations used a 1–D Lagrangian MHD code which contains a self-consistent circuit model capability. The circuit model of the helical flux compression generator, current opening switch and current interrupter was based on numbers provided by VNIIEF, including inductance of the generator and transmission lines and time-dependent resistance of the current opening switch and current interrupter. With the load assembly dimensions specified, the final current produced by the generator is the only parameter of variation in the calculations. All calculations used the Steinberg-Guinan strength model and LANL Sesame EOS for aluminum 1100-O.

A. Desired Experimental Outcomes

RD-0 has two objectives. First, Visar will measure the velocity of the bare liner to compare with the calculated velocity from the generator/load assembly circuit model. Second, the desired liner impact velocity is 204 m/s, the middle of the incipient spall range.

For RD-1, the desired liner impact velocities bracket the incipient spall velocity range at 198 – 200 m/s for Target 1 (outer radius 43 mm) and 208 – 210 m/s for Target 2 (outer radius 45 mm).

For RD-2, the desired target impact velocity is 212 – 215 m/s, slightly above the incipient spall velocity range.

B. Parameter Studies

For the parameter study detailed in this section, the generator current was varied between 9.6 MA and 9.9 MA in increments of 0.1 MA, providing a 3% total variation (1% per increment). All times are measured from time t = 0 of the current opening switch.

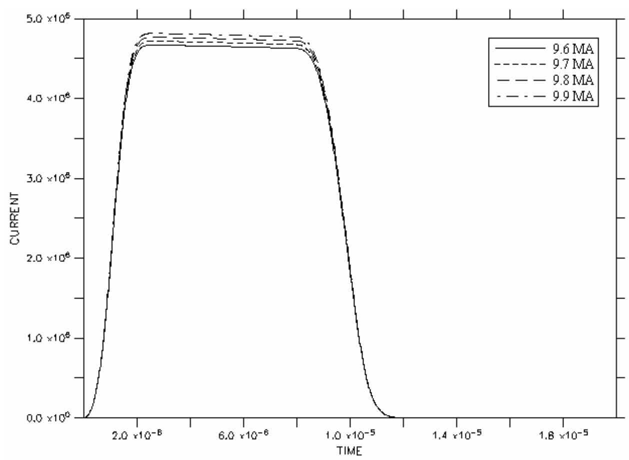

Figure 1. Calculated load-region current (A) variation.

For a given generator current, the load-region current and initial liner motion is the same for all 3 experiments. Duration of the current pulse in the load region is approximately 10 µs. Variation of load-region current as a result of generator current variation is shown in Figure 1, with the maximum listed in Table 1, column 2. In all cases, maximum current occurs at 2.62 µs. Maximum load-region current is slightly less than half of the generator current. The current remains almost constant for approximately 6 μs.

Figure 2 shows variation of velocity of the liner inner surface (as a function of radius) with respect to variations in generator current. Table 1, columns 3 and 4, shows the variation in the velocity and time of liner impact on targets located at 45 and 43 mm, respectively. This data indicates that a generator current of 9.75 MA is needed to obtain the desired target impact velocities.

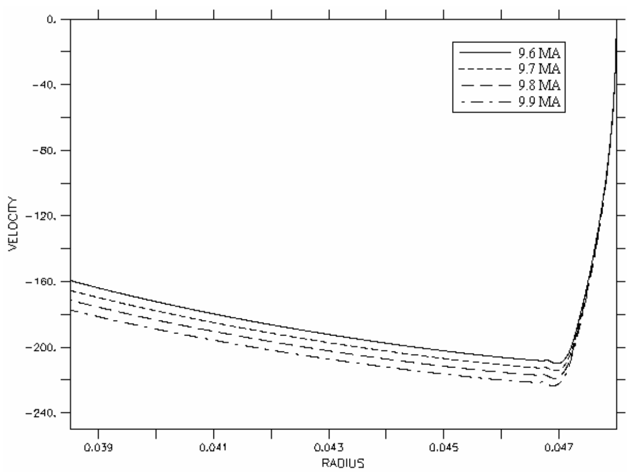

Figure 2. Calculated variation of velocity (m/s) of liner as a function of radius (m).

Table 1. Variation of load region current and impact velocities and times at 45 mm and 43 mm radii.

Gen. Current (MA)	Max Load Current (MA)	Impact Velocity (m/s) and Time (μs) @ r=45 mm		Impact Velocity (m/s) and Time (μs) @ r=43 mm	
9.6	4.669	202.1	191.8	191.8	30.00
9.7	4.718	206.8	196.8	196.8	29.46
9.8	4.766	211.5	201.8	201.8	28.92
9.9	4.815	216.3	206.8	206.8	28.40

C. Load Behavior with 9.75 MA Generator Current

Results of calculations using a generator current value of 9.75 MA are shown in Figures 3 – 6. Velocity of the liner to target impact is shown as a function of radius in Figure 3 and as a function of time in Figure 4. Both RD-2 targets are located at the same outer radius. Table 2 lists the velocities and times of liner impact on the targets. These impact velocities satisfy the stated design criteria.

The free-surface velocities of the targets as a function of time are shown in Figure 5, with maximum velocities and corresponding times listed in Table 3. Note that there is no spallation model in the code used in the calculations. Instead, failure is attributed to melting of the material in cells with high volumetric strain. The code accurately predicts breakout of the shock wave and the location of the potential failure of the solid material. However, it does not attribute the failure to the correct phenomenon and does not correctly account for the energy necessary for void nucleation, growth and coalescence, making the calculation after the onset of damage suspect.

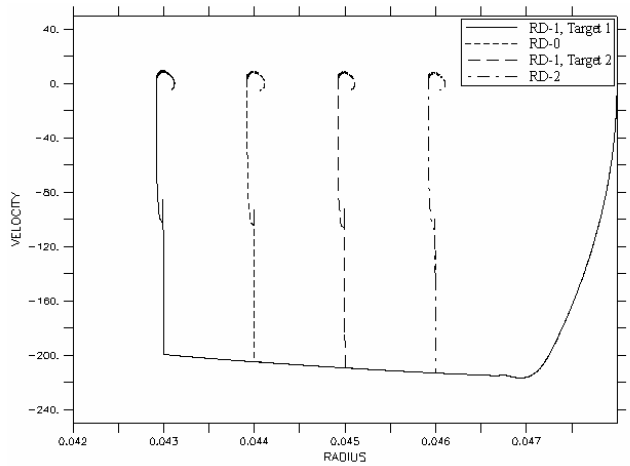

Figure 3. Calculated velocity (m/s) of liner to target impact as a function of radius (m).

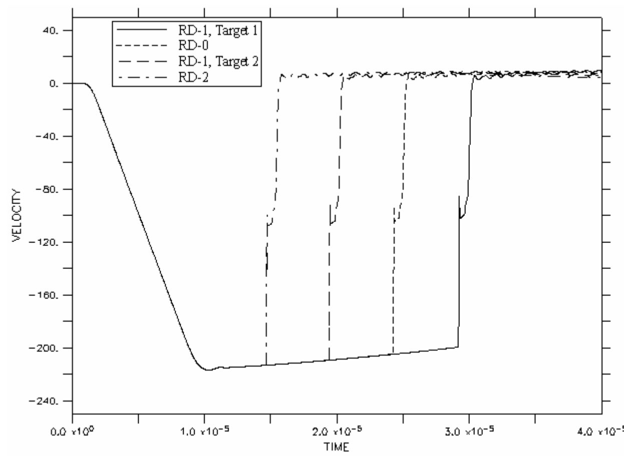

Figure 4. Calculated velocity (m/s) of liner to target impact as a function of time (s).

Table 2. Velocities and times of impact of liner on targets for 9.75 MA generator current.

	Radius (mm)	Impact Velocity (m/s)	Impact Time (μs)
RD-1, Target 1	43	199.3	29.18
RD-0	44	204.5	24.24
RD-1, Target 2	45	209.1	19.40
RD-2	46	213.0	14.66

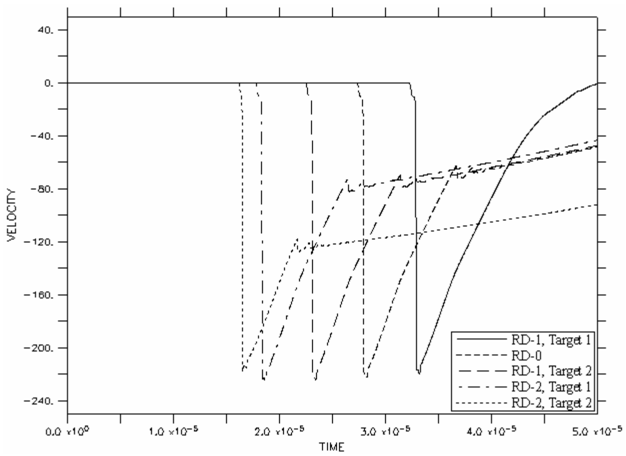

Figure 5. Calculated target free-surface breakout velocity (m/s) as a function of time (s).

Table 3. Peak free-surface breakout velocities and times for 9.75 MA generator current.

	Radius (mm)	Breakout Velocity (m/s)	Breakout Time (μs)
RD-1, Target 1	23	219.4	33.22
RD-0	24	222.2	28.28
RD-1, Target 2	25	224.1	23.44
RD-2, Target 1	26	224.8	18.70
RD-2, Target 2	36	217.7	16.60

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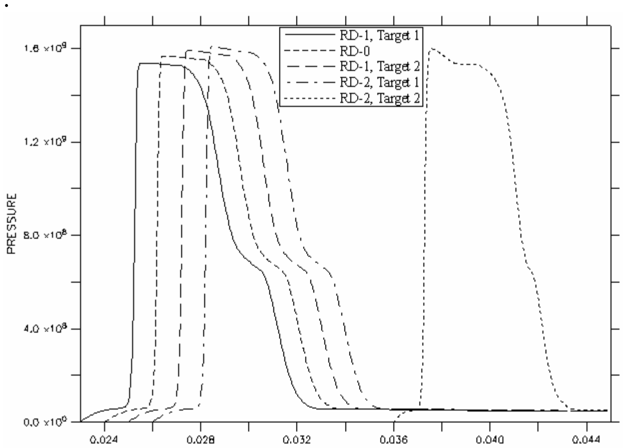

Figure 6. Calculated target free-surface incident pressure (Pa) as a function of radius (m). Note: times vary.

The incident pressure at the free surface of the targets as a function of radius is shown in Figure 6. The times of the indicated pressure pulses vary.

The outside of the liner is heated to a temperature of not more than 480° K, well below the melting point of Al-1100-O (~1200° K). It does, however, produce a small gradient (1.5%) in the liner density. Thus, the imparted pressure wave tapers off slightly on the back side.

IV. CONCLUSIONS

In planar geometry, incipient spall in 1100-O aluminum occurs for impact velocities in the range of 198 – 210 m/s. Currently, due to lack of any evidence to the contrary, this is also the best guess for incipient spall in a cylindrical geometry. Determining the incipient spall impact velocity range is one objective of this experimental series. The other objective is to determine the effect of plastic work on energy dissipation and shock wave propagation.

Liners will be in free flight at impact with the targets, with no driving current remaining. Variation in impact velocities is obtained by varying locations of the targets. The modular design of the experiments allows for adjustment of the currents for RD-1 and -2 based on the results of RD-0, to achieve the targeted impact velocities.

The major area of concern for this series of experiments is sensitivity of impact velocity and time to energy input. Obtaining impact velocities between 198 m/s and 210 m/s necessitates a precise drive of the impactor. In addition, recovery of the target portions of the load assembly is an absolute necessity, since post-experiment metallographic analysis will provide a significant portion of the information about void nucleation and growth behavior.

Objectives of the following 7 experiments include continued study of incipient spall and study of the closure of the voids after they have formed. Recovery of the target for post-experiment metallographic analysis and the Visar and Faraday diagnostics will continue to be of high importance in the experiments, while radiography will become increasingly important as the impact velocities continue to increase above the incipient spall regime.

VI. REFERENCES

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LA-UR-05-44